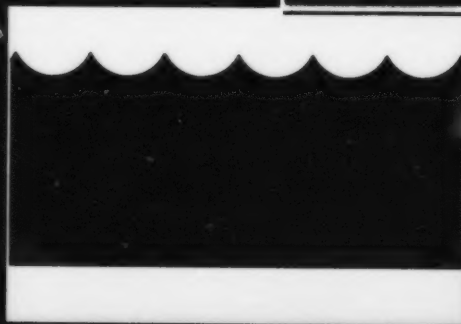
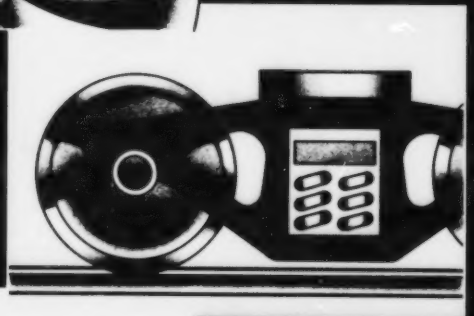
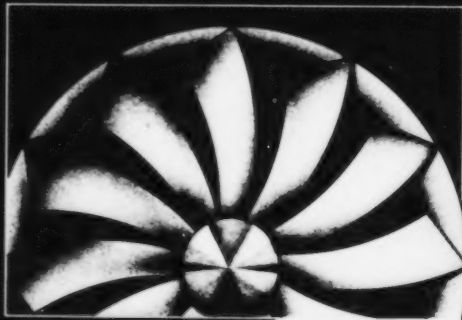




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Division of Mechanical Engineering Annual Report 1987/88



Canada

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**DIVISION OF MECHANICAL
ENGINEERING
ANNUAL REPORT
1987/88**

**DIVISION DE GÉNIE
MÉCANIQUE
RAPPORT ANNUEL
1987/88**

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Foreword

The Division of Mechanical Engineering — 1987/88 in Review

After the various changes in the R&D program and adjustments in the operational structure of the Division of Mechanical Engineering (DME) in 1986/87, 1987/88 became a year of quietly redirecting DME's program, building on our existing strengths of expertise, unique experimental facilities, and excellent rapport with clients from the private and public sectors.

Only one minor organizational change was made; the machinery and rotor dynamics work was transferred from the Division's Engine Laboratory in Ottawa to the Tribology and Mechanics Laboratory in Vancouver. This transfer complemented the applied mechanics research activity of our Vancouver Laboratory and provided more readily accessible expertise to our clients in Western Canada. In the meantime, the western branch of the Systems Laboratory, formally established in Vancouver in 1986/87, continued successfully to expand its activities.

A new major interdivisional Transportation Program was proposed and accepted by Senior Management and Council. A careful analysis of the importance of transportation on the Canadian economy clearly indicated a large potential for an overall reduction of costs to operators of transportation equipment, as well as to governments for maintaining the Canadian transportation infrastructure. Since more than half of DME's activities is related to transportation technology, this interdivisional program will have an important effect on the divisional R&D program.

In 1987/88, a comprehensive review of all divisional activities was conducted, which included an internal audit, a program evaluation, and a peer review. The latter involved three separate subcommittees, corresponding to the three traditional disciplines of mechanical engineering: applied mechanics, hydrodynamics, and thermodynamics. The three subcommittee chairmen (Dr. J. Mølgård of Memorial University, Dr. P. Camu of Lavalin International Ltd., and Mr. H.C. Eatock of Pratt & Whitney Canada Inc., respectively), together with the two members of Council (Mr. K. Hammill of Omark Canada

Ltd. and Dr. J.H. de Leeuw of University of Toronto), composed the DME Review Committee of Council. Although the final report of the Review Committee would not be presented to Council until September 1988, discussions between review subcommittee members and divisional staff, as well as several meetings of the subcommittee chairmen with divisional management, provided immediate feedback for the setting of priorities for DME.

Perhaps the most important recommendation concerned the balance between the long-term strategic research component of DME's program and the applications-oriented engineering work for/with external clients. It was recommended that the level of strategic research should be at least 30% of the total DME effort. While this target of 30% has been accepted as an operational objective of the Division, this must be seen in the perspective of an earlier decision to increase the level of external revenue. This will mean that more emphasis will be placed on attracting collaborative, strategic or generic research projects, with our external partners contributing resources, either directly as financial support or "in-kind" (equipment, personnel, data, etc.).

The Statement of Resources and Expenditures on page 5 shows that the level of expenditures recovered from external sources has already increased from 10.5% in 1986/87 to 14.2% in 1987/88. This trend is expected to continue to at least 20% and would rise to an even higher level, if no limitations are set on the use of external revenues to hire staff.

In future years, 1987/88 may very well be seen as a turning point for DME. After the severe cutbacks in 1986/87, new goals were set and, assisted by the in-depth external review of the Division, new opportunities were seen. DME has an important role in responding to the technological problems and opportunities in such areas as transportation, industrial technology, and energy flexibility. The expertise and dedication of our staff form an essential part of the national resources available. Moreover, there is a strong commitment from all our staff to carry out these tasks in cooperation and in collaboration with partners from industry, universities, and government.



J. Ploeg
Director

Introduction

Engineering Research Areas and Services

Raison d'être

The Division of Mechanical Engineering (DME) is one of fourteen research divisions of the National Research Council. It serves Canada as a *National Laboratory* to develop and apply mechanical technologies needed for solving important national problems. It also helps the country pursue economic opportunities by helping Canadian firms develop and use proprietary technologies.

As with all of NRC's divisions, DME has a *residual* mandate, to work only in fields that are not being investigated effectively anywhere else in Canada. Program areas are chosen that need the breadth and depth of research effort that only a national laboratory can provide. The Division concentrates on operating large-scale mechanical engineering facilities; conducting long-term exploratory research programs; developing major new generic technologies; and developing technologies that are germane largely to governments, such as transportation, safety, defence, national standards, and energy.

DME is Open for Business

Canadian companies can make various types of arrangements for the use of DME's facilities and expertise. These include

- customized research and development projects
- specific testing, analysis, verification, and calibration
- collaborative research projects (several partners share financing, facilities, equipment, expertise, or advice)
- co-funded projects jointly controlled and managed by DME and a partner
- access to major engineering facilities and installations
- opportunities for company researchers to work within DME with our specialists
- licences to know-how and patents

Fees

DME charges for certain services, but not for others. In general, where the Division provides a client with technical information or with results that are of exclusive use to the company, full costs are charged for time, equipment, and the facilities. Where DME provides a client with technical information or with results that can be shared with other Canadian firms, fees are generally not charged.

Priorities

DME conducts programs in three main areas of application: *transportation, industrial technology, and energy flexibility*. These areas constitute the Division's priorities as of 1988/89 and will remain so during the planning period that extends to the end of the fiscal year 1991/92.

Programs

DME activities are grouped into six program areas: *Computer Technology, Manufacturing Technology, Machine Mechanics and Vehicle Dynamics, Propulsion Systems, Industrial Thermodynamics, and Coastal and Offshore Engineering*.

These are *generic technology* areas whose results cut across a multitude of application areas. For example, computer technology is being developed to help Canadian manufacturers improve their scheduling and control methods, to help lakehead coal shippers improve their terminal operations and transportation planning, and to help Canadian aircraft operators analyze maintenance problems in their gas turbine engines.

Because NRC is not constrained to serve any one sector exclusively, such as agriculture, communications, or transportation, it is able to pursue technological areas that have the broadest possible application potential within Canada.

The research projects underway within DME are as follows:

Computer Technology

- development of methods for computer modelling of complex machinery, vehicles, and industrial processes
- development of decision support systems for industrial management of scheduling, control, and optimization of resources
- application of artificial intelligence to industrial problems in process control, engine health monitoring, vehicle regulations, and control systems

Manufacturing Technology

- development and application of laser material processing methods
- machining and joining of advanced structural materials
- development of methods and applications in flexible automated manufacturing
- development of methods for electron beam welding
- application of high pressure water jet and abrasive jet cutting

Machine Mechanics and Vehicle Dynamics

- research into the methods and facilities for analyzing and controlling the dynamic behaviour of trains
- development of methodologies to measure transient axle loads of highway trucks and to determine their stability parameters
- research into improved methods of lubrication and of reducing friction and wear
- development of methods to detect and characterize machinery noise and vibration, and to predict and avoid breakdown

Propulsion Systems

- aerodynamics and thermodynamics of gas turbine and reciprocating engines
- determination of engine performance parameters

- development of engine health monitoring methods and systems
- development, operation, and calibration of engine test cells
- optical diagnostics and mathematical modelling of combustion processes
- fuel, combustion, and engine-design interrelationships
- advanced ceramic engine components and off-specification fuels
- development of fuel standards and specifications

Industrial Thermodynamics

- development of analytical models of continuous combustion and fluid mechanical systems
- thermodynamics of heat pumps designed for low temperature differentials
- development of computational methods for heat transfer analysis
- applications for heat pipes
- countermeasures for snow and ice ingestion by mechanical equipment
- detection, prevention, and removal of ice accretion on surfaces
- machinery operating problems at low temperatures

Coastal and Offshore Engineering

- analysis and scaled reproduction of complex wave forms and wave spectra
- development and operation of Multidirectional Wave Basin and Coastal Wave Basin facilities
- development of methods for computational and hybrid (computer/physical) models of rivers, estuaries, and harbours
- analysis and modelling of wave effects on shorelines and in harbours
- predication and control of sediment transport and deposition
- development of ice modelling techniques and the study of ice forces on structures

Future Initiatives

Transportation technology is becoming increasingly important. During the year under review, DME, together with the National Aeronautical Establishment and the Institute for Marine Dynamics, began to integrate its research into the NRC-wide Transportation Program. This will be intensified in the future, with the Transportation Program providing a user- and applications-oriented "drive" for many DME programs. Emphasis will be placed on engine health monitoring, computational numerical modelling, and the application of tribology and methodologies in acoustics and machine vibrations.

In *Computer Technology*, DME will emphasize artificial intelligence methods and their application to transportation, manufacturing, and resource industry problems.

In *Manufacturing Technology*, DME will emphasize the treatment and processing of materials, e.g., by surface modification of steels, with relatively less emphasis on the production of such materials. Production methods for advanced composites will be de-emphasized. Work on manufacturing methods for complex propulsion system components, such as gas turbine engine blades, will continue to be important. So too will flexible manufacturing systems, computer-integrated coordinate measuring machine techniques, and novel cutting methods.

In *Machine Mechanics and Vehicle Dynamics*, increased emphasis will be placed on applying highway vehicle dynamics methods to the development of better truck regulations and to the prevention of road wear. Contributions will be made to the Transportation Program (previously mentioned) in acoustics and vibrations, and in tribology. Greater applications are foreseen for numerical modelling.

Propulsion Technology will increasingly emphasize combustion processes and the use of new materials, such as ceramics, in engines. Alternative fuels will continue to be an important component of this work. Engine health monitoring will be a major application area.

Industrial Thermodynamics will emphasize analytical modelling of combustion and fluid mechanical systems, heat transfer processes, and the thermodynamics of heat pumps.

In *Coastal and Offshore Engineering*, growing emphasis will be placed on computational modelling. This will be increasingly correlated with other related work elsewhere in NRC and Canada as part of NRC's Transportation Program. Techniques will continue to be studied and applied to the continuing effort to protect coastlines and harbours from erosion or sedimentation.

Finally, the operation and ongoing improvement of NRC's National Facilities for mechanical engineering will continue as a priority to maintain the Division's standard of excellence in engineering.

Statement of Resources and Expenditures

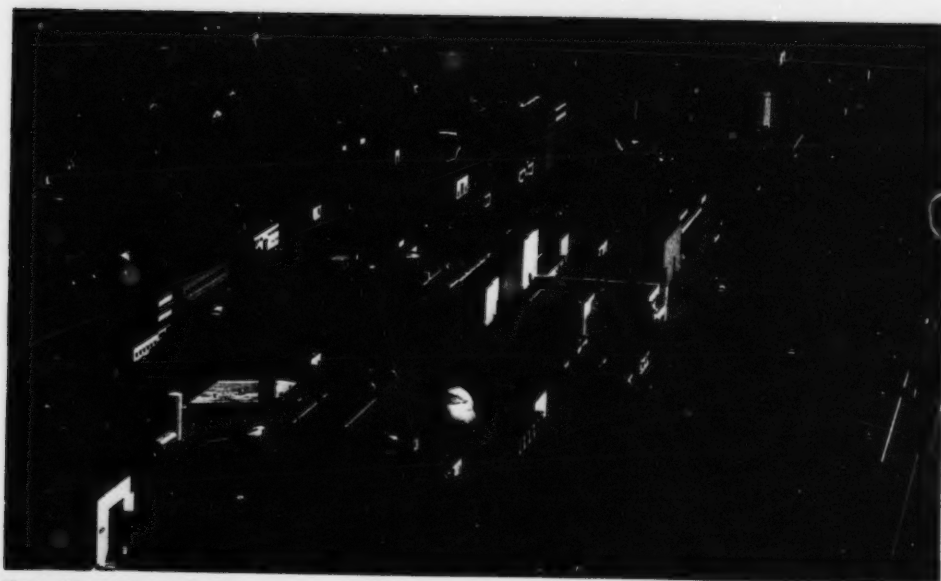
	1 April 1988	1 April 1987
Divisional Staff Level	252	261



Percentage Staff by Research Area (1988 figures)	Applied Mechanics	45%
	Thermodynamics	34%
	Hydrodynamics	14%
	Administration & Support Services	7%

Divisional Expenditures (\$1000's)	1987/88	1986/87
Operating	2 813	3 223
Major Capital	1 012	1 679
Minor Capital	2 029	2 902
Salaries	10 745	10 400
Incremental expenditures, recovered from other government departments	1 971	1 396
Expenditures recovered from nongovernment sources	783	702
Total	19 353	20 302





Montreal Road, Ottawa, Ontario



Alert Road (Uplands Airport), Ottawa, Ontario



Westbrook Mall, Vancouver, British Columbia

Computer Technology

The Division's Systems Laboratory develops computer-based technology to improve industrial productivity. It emphasizes the development of decision support systems for assistance in industrial operation and management, advanced information system uses for improved "integration" in industrial operation, and modelling of dynamic systems for improved design in engineering and transportation systems.

Resource Industry Applications

In the Ottawa and Vancouver branches of the Systems Laboratory, integrated computer-based decision support systems have been developed for evaluating facility design in the resource industries, as well as assessing alternative operating and control practices. Expertise is available to solve bulk material handling and capacity flow problems. Projects are underway in the mining, forestry, and grain handling sectors.

A scheduling aid-and-information system for the berthing of grain vessels in the port of Vancouver was developed in collaboration with the *B.C. Grain Shippers Clearance Association*. A prototype knowledge-based system for the selection of excavating equipment for surface mining was built in collaboration with the Department of Mining and Metallurgical Engineering of *McGill University*. A project is continuing with *Valmet-Sentrol Ltd.* (Toronto) to develop a self-diagnostic, self-correcting system for the control of paper-making equipment.

Computer Modelling and Simulation of Engineering Systems

Computer modelling of dynamic systems is used as an engineering tool to study the design of machinery and complex engineering systems. Typical problems are related to aircraft, ground vehicles, and industrial equipment. These systems are described by differential equations; problem analysis requires solution of large, coupled sets of these equations. The Laboratory has developed a methodology for simplified production of models and their subsequent

analysis. A specialized processor (Applied Dynamics AD100) is used for real-time differential equation solution.

The project in the area of engine health monitoring is continuing. This involves the use of computer models, information systems, and artificial intelligence techniques to detect, analyze, and predict faults for gas turbines. To date, a model of a healthy T56 engine has been built. Data is now being added to the model to simulate unhealthy engine conditions.

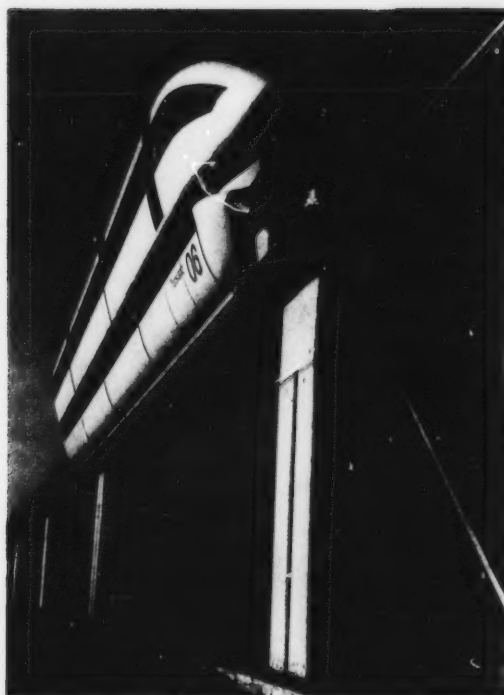
A study has been completed in the advanced control of large space structures. Large structures, such as space stations, are characterized by mathematical descriptions with many degrees of freedom and uncertain parameters. Improved adaptive control procedures have been formulated.

Ground Transportation Systems

A new group was formed in the Systems Laboratory during 1987/88 to focus on the development and use of computer software to address general and customer-specific requirements of the rail and road transportation industry. A study was completed on the expected stiffness and torsional vibration of the Wheel, Bearing, and Brake Facility for DME's Vehicle Dynamics Laboratory. The group obtained a contract for the study of a rapid transit system between Miami and St. Petersburg in conjunction with the *Canadian Institute of Guided Ground Transportation*. This project will use and augment the considerable expertise already developed by the Laboratory in this area.

Intelligent Knowledge-Based Systems

The intelligent knowledge-based system resources, reported in the 1986/87 Annual Report, were transferred to the Division of Electrical Engineering to consolidate NRC's activities in the discipline of artificial intelligence. Nevertheless, artificial intelligence methodology is still being used and applied by the Systems Laboratory as part of its work on technical problems in several areas within the Division.



Prototype Transrapid TR-06 Maglev system — a high-speed passenger transportation system under study for the Los Angeles/Las Vegas traffic corridor.

Canadian Consulting in High-Speed Passenger Transportation Systems

High-speed guided ground passenger transportation has begun to attract interest in North America for a number of high traffic density corridors. There is considerable promise in these corridors for an economically viable and travel-time-competitive alternative to travel by automobile and aircraft.

One of the prime North American corridors is between Los Angeles and Las Vegas. Early planning and technological assessment is being led by the Department of High Speed Train Development, Las Vegas, NV, with the support of the U.S. Department of Transportation. Some key parts of the technical consulting work have been done by Canadians.

The *Canadian Institute of Guided Ground Transportation* (CIGGT) of Queen's University, Kingston, Ont., was awarded an open-bid contract for specified technical aspects of the High Speed Ground Transport System Technology Assessment Project. The work consisted of assessing a variety of high-speed guided ground transport systems and their associated guideway/track infrastructures for their application potential within the Los Angeles/Las Vegas traffic corridor.

To complement the Queen's University staff specialists assembled for the project, CIGGT contracted a NRC professional from DME's Systems Laboratory to serve as a principal researcher for the project. The project requirements included a technological assessment of current performance, development status, and recent application studies of high-speed systems, developed or designed in various parts of the world. The work included theoretical analyses and on-site investigations of experimental and operational installations of high-speed systems in North America, Europe, and Japan.

The combination of skills in economic analysis and project management brought to the project by Queen's University staff members, and in systems analysis and technology assessment brought by DME's staff member, provided a technically well-balanced group that completed the project with a high level of thoroughness and competence. This has since led to additional transportation technology contracts from U.S. sources for Canada involving CIGGT/DME collaboration. NRC's ability to bring advanced analytical expertise into a contracted project in collaboration with universities and industries can help to increase Canadian competitiveness in securing technology-based open-bid contacts internationally. Since its release in 1987, the final report for the project has been widely referenced within the North American transportation community.

Manufacturing Technology

Electromechanical Technologies

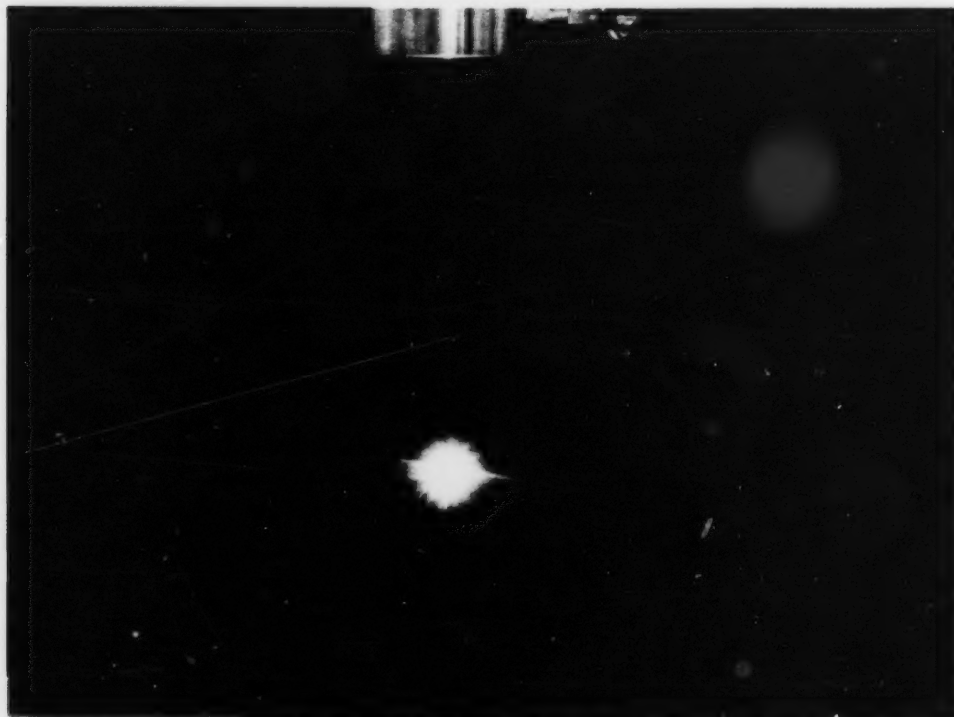
The Division's Manufacturing Technology Centre (MTC) conducts applications development work in laser, electron beam, and high-pressure water jet technologies, with emphasis on helping Canadian companies to improve their productivity and to generate new products through the innovative use of these new technologies.

Laser Surface Alloying

Selective laser surface alloying can be used economically to improve the performance of parts subjected to aggressive environments, without resorting to expensive and scarce materials. Typical applications include diesel engine valves and seats, the leading and trailing edges of turbine blades, and parts for furnaces and boilers.

Research conducted during 1987/88 in collaboration with the *Canada Centre for Mineral and Energy Technology (CANMET)* of Energy, Mines and Resources Canada demonstrated that, by using lasers, the surfaces of mild steels can be alloyed successfully with chromium to obtain properties comparable to those of stainless steel. Tests conducted on laser surface alloyed specimens showed the high-temperature oxidation rate had been decreased significantly. Information concerning the research was disseminated through presentations at conferences in Winnipeg and Toronto.

MTC, the *Ontario Research Foundation*, and *Energy, Mines and Resources Canada* are collectively investigating the potential of laser surface alloying for improving the corrosion resistance properties of aluminum bronzes. Binary aluminum bronzes will be



Laser transformation hardening of bobsled runners for the Canadian Amateur Bobsleigh and Luge Association. Laser hardening is one of many new methods being applied by MTC to specific materials problems.

surface alloyed with iron to obtain the ternary alloys that are more corrosion resistant than normal aluminum bronzes, without affecting the preferred bulk mechanical properties of the binary alloys. The properties of the modified surfaces will be characterized to document the improvements.

Research is also being conducted to incorporate oxygen-active elements (such as chromium, yttrium, and aluminum) in steel substrates, to impart surface properties approaching those of superalloys. Industrial partners are being sought to collaborate in this research.

Laser Welding

Work continued in this area during 1987/88. Industrial projects ranged from welding heavy brake assemblies for trucks to delicate small components for communication devices. Challenging problems solved for other research laboratories included the welding of a very fine stainless steel bellows assembly for NRC's Division of Chemistry.

Electron Beam Welding

The full 42-kW output of MTC's electron beam welder was employed to weld 10-cm-thick chrome molybdenum steel. The welds were made in a single pass, while travelling at a speed of 20 cm/min and without the addition of filler metal. The high quality weldments developed at MTC are being evaluated by CANMET laboratories of Energy, Mines and Resources Canada against other technologies, such as narrow gap welding.

Among the numerous projects undertaken for Energy, Mines and Resources Canada was the development of a repair procedure for salvaging damaged titanium turbofan blades. When this procedure is fully developed, it will provide the Orenda Division of Hawker Siddeley Canada Inc. with an economical alternative to replacing damaged blades with expensive new ones.

Water Jet Cutting

Applications investigated for clients ranged from cutting frozen fish and vegetables to

cutting advanced composite materials for the aerospace industry. Work continues on the evaluation of the new high-pressure intensifier, under development by VFT Systems Inc.

Computer-Integrated Manufacturing

A significant trend in manufacturing research in industrial countries such as United States, Japan, and Germany is towards manufacturing systems that are flexible enough to adapt quickly to changing market needs. To assist Canadian parts manufacturers exploit this technology, MTC is conducting research into flexible computer-integrated systems (CIM) that cover the design, machining, and inspection of parts.

Adaptive Manufacturing Cell

The productivity level and flexibility of the cell was improved by the development and upgrading of software during 1987/88. The cell is now capable of running unattended or in various other modes to suit the productivity needs of the cell user. Parts loaded into the machine, by an automatic handling device such as a robot, are probed to determine their true position. The cell control system then modifies all the NC files to correct programs for up to six axes of machining operations. This ensures a very high degree of repeatability on finished parts. The system permits fine finishing on sculptured parts that would normally have to be done by hand. Its reliability has been demonstrated by machining a batch of 60 complex turbine blades with a high degree of dimensional repeatability and with no rejects. These parts were required for an engine testing program conducted by DME's Engine Laboratory with an industrial partner.

Computer-Aided Inspection

MTC has linked its coordinate measuring machine to its CAD/CAM system, to obtain inspection data for sculptured parts produced in the adaptive manufacturing cell. A direct comparison now can be made of the produced shape against the design requirements.

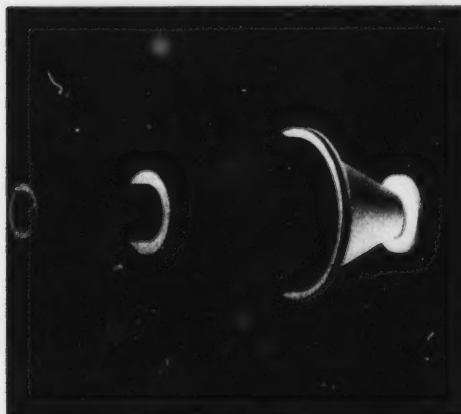
Work was started on a program to calculate parameters of airfoil shapes based on section information, and will include features

such as datum error, chord length, angle, and thickness, as well as edge thickness. When this work is completed it will allow a coordinate measuring machine to evaluate a blade's geometry in a manner similar to traditional inspection approaches, but to a higher degree of precision.

Computer-Aided Design and Engineering

Two major changes in direction were taken by MTC's Engineering Design Section. The central computer-based CAD/CAM system was replaced by a distributed cluster of VAXstations that integrates design, engineering, and manufacturing data bases. This cluster will also permit the designers to communicate directly with other workstations within NRC and elsewhere. Secondly, steps were taken to upgrade capabilities to incorporate advanced materials into the design and manufacture of new products and component parts. Moving into this specialized field enables MTC to offer clients greater design possibilities. It also augments NRC's overall thrust into advanced materials applications development.

Some of the design projects of the past year included the Wheel, Bearing, and Brake Research Facility for the DME's Vehicle Dynamics Laboratory, ceramic inserts for diesel engine exhaust valve experiments in the Division's Fuels and Lubricants Laboratory, atmospheric combustors for nozzle and fuel design experiments in the DME's Gas Dynamics Laboratory, a rotating cryostat for advanced materials development in the



CAD model of an atmospheric combustor designed and built by MTC for the Gas Dynamics Laboratory, utilizing ceramic components.

NRC's Division of Chemistry, and a space frame vertical actuator for vision system experiments in NRC's Space Division.

Advanced Materials

The Manufacturing Technology Centre no longer conducts research into the manufacture of advanced composite materials, but continues to develop methods of machining and cutting such advanced materials.

Ceramic valve components were machined using a vertical-spindle CNC machining centre, employing a separate coolant tank, pump, and delivery system designed and built by MTC. The CNC contouring system was used to obtain the desired shapes and sizes. A CNC tool and cutter-grinder was also utilized as a cylindrical grinder to finish certain faces and diameters of the components.

As well, an up-to-date information base has been maintained on ceramic and metal matrix composites during 1987/88. A Divisional Report was published reviewing the development of artificial composites containing fibres or whiskers in metallic or ceramic matrices for high temperature applications.

Manufacturing Support Systems

The Division's Systems Laboratory is concerned with the development of specific software tools and techniques for manufacturing operations in the areas of management, planning, resource utilization, and production control.

In the past year significant progress has been achieved in constraint-based scheduling. This logic-based system combines procedural and artificial intelligence methods to make decisions, depending on rules and constraints. A small prototype system was built in conjunction with *Alcan International Ltd.* for the scheduling of heat treatment furnaces. Work is in progress with *Huyck Canada Ltd.* to develop a generalized constraint-based scheduler for the company's paper mill felt manufacturing operation.

A glossary for industrial automation terms was compiled by the Laboratory as a tool for manufacturing operations, and was submitted to the *International Organization for Standardization* for adoption as an international standard.

Machine Mechanics and Vehicle Dynamics

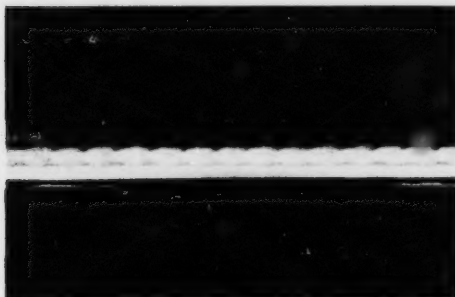
Tribology

The Division's Tribology and Mechanics Laboratory (Vancouver, B.C.) performs research to determine friction, wear, and lubrication characteristics of materials and components of mechanical systems involving sliding, rolling, and impact motion in scaled tests simulating end-use conditions. Projects, frequently involving physical experiments complemented by theoretical modelling and field testing, are carried out to solve industrial and transportation-related problems.

Rolling Contacts

The emphasis of research during 1987/88 continued to be in the area of rail/wheel contacts. Following numerous tests and theoretical investigations, a mechanism of corrugation initiation and growth was determined. This established the primary cause of the short-pitch corrugations adversely affecting ride quality on the Vancouver SkyTrain. Measures to alleviate the corrugation problem have been recommended.

Progress was also achieved with preventive rail grinding for the heavy haul railways. The shape of rail profiles that delays the onset of contact fatigue, but allows some steering of freight car trucks, was established for straight track and for mild as well as sharp curves. A template gauge was designed and fabricated to allow on-site inspection of preventively-ground rail profiles. Laboratory wear tests of rail steel specimens of varying metallurgical cleanliness were completed and are currently under evaluation.



Wear corrugations on rails of the Vancouver SkyTrain.

Sliding Contacts of Nonmetallic Materials

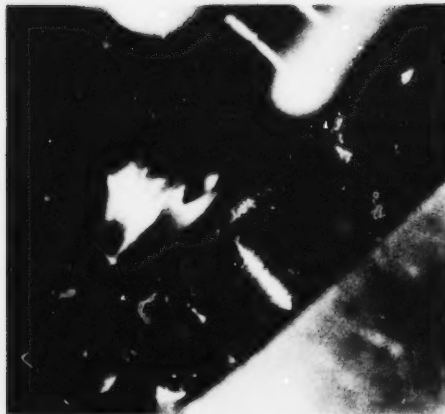
Extended, high-speed simulation tests at 450°C were made for Pratt & Whitney Canada Inc. to verify promising low-wear ceramic/metal combinations for flexible element, turbine gas-path seals. A new reciprocating friction and wear tester was commissioned as an important tool for high-temperature (up to 600°C) tribological assessment of experimental ceramic materials to be used in diesel engine and other machine components, as part of NRC's Engineering Ceramics Program. The Laboratory is also participating in the VAMAS (Versailles Project on Advanced Materials and Standards) international round-robin aimed at developing wear test standards for advanced materials.

Basic aspects of *in-vacuo* friction behaviour of RMS brake material have been studied, in anticipation of industrial support for research in alternative materials suitable for extended use in space. Proposals have been made to establish a space tribology capability within the Laboratory to support the development of Canadian robotic space mechanisms.

Wear and Friction in Vibratory Contacts

In a basic study completed in 1987/88, adhesion and fatigue were shown to be the main wear mechanisms in combined impact and reciprocating contacts of steel versus steel and steel versus brass specimens. Wear was found to increase proportionally with impact energy in two stages, separated by a transition from mild to severe wear. Joint studies with the Centre for Frontier Engineering Research on sucker rod/tubing wear in deviated oil wells are in progress and a NRC/university/industry collaborative research project on steam generator tube wear is being initiated, with the financial support from Atomic Energy of Canada Limited and the Natural Sciences and Engineering Research Council of Canada.

The mechanisms of friction-induced vibration are under investigation, and testing equipment for a joint NRC/University of British Columbia study of friction welding is being improved and instrumented for the measurement of friction forces.



Impact fretting wear of research test specimen. Note the worn surface caused by removal of material owing to impact and rubbing of the specimen by the striker.

Fluid Film Tribology

Research on the thermal effects in tilting pad journal bearings has continued, and a paper was presented, confirming that the oil film cross-coupled coefficients are small. A second study, in collaboration with a visiting scientist from the Polish Academy of Sciences, showed good agreement between theory and experiment. Work has started on the measurement of bearing flexibility and damping characteristics.

A study on leakage problems associated with the oil well seal assembly of vertical bearing units is also being conducted in conjunction with *General Electric Canada Inc.* A project concerning the effect of ring design on the rate of oil delivery from the oil ring lubricator has been completed.

Three new programs of research in fluid film tribology are being pursued: modelling of large journal bearings, mixed film operating conditions, and the damping properties of elastomeric bearings. Various Canadian companies have expressed interest in the programs and their direct involvement in the work is anticipated in the near future.

Machine Mechanics

Machinery/Rotor Dynamics

This work was transferred from the Division's Engine Laboratory in Ottawa to the Tribology and Mechanics Laboratory in Vancouver during 1987/88.

A new theoretical technique for shaft critical-speed analysis has been developed for micro- or personal computers using a numerical algorithm with overflow control. Machinery health monitoring and detection techniques of rolling element bearing incipient failure through vibration analysis are being investigated, with some expansion into tribological fields. Studies on machinery vibration treatment techniques were initiated in cooperation with *Cullen Detroit Diesel Allison Ltd.*, with the objective of isolating diesel generator set vibrations from Canadian navy ship hulls.

Machinery Noise Source Identification

Sound intensity measurements are being used increasingly in many Canadian industries such as mining, textile, forestry, and utilities, as well as in national defence applications. The Engine Laboratory is currently researching sound intensity measurement techniques and their application in determining sound power radiated by machinery in its actual operating environment.

Estimates of sound power using sound intensity measurements can be uncertain owing to interference from reflecting surfaces and extraneous sources of noise. The Laboratory recently has completed a study on the accuracy of sound power estimates of one small-sized and two medium-sized machines under varied acoustic environments. Several indicator criteria for ascertaining the quality of measurements are currently being examined.

As well, the calibration of sound intensity probes without the use of spacial acoustic facilities is being investigated. Preliminary work on a two-microphone probe using the gating technique has been completed, and further work is in progress using the gating technique as well as a standing wave tube.

The Engine Laboratory has provided assistance in the use of sound intensity techniques to *Ontario Hydro*, *Can-Car Pacific* (*Hawker Siddeley Canada Inc.*), and *Energy, Mines and Resources Canada*. Because of the Laboratory's long-standing reputation in this area, it provides representation to working groups of the International Organization for Standardization, the International Electrotechnical Commission, and the American National Standards Institute.

Mechanically-Controlled Machines

Certain types of industrial mechanical equipment can be mechanically powered and controlled so that weight, size, complexity, and cost savings can be realized. The Tribology and Mechanics Laboratory is presently developing such equipment to meet some of the future needs of the Canadian forestry industry.

A second prototype of the Laboratory's patented, slack-pulling and "lock-up" skyline yarding carriage has been designed. Sized for steep slope logging or for thinning and selective cutting, it will be built and field-tested in the coming year. This is the first such carriage capable of operating uphill or downhill without additional cables or radio controls.

A fundamental study is also being initiated to examine the basic principles of control of mechanical devices by simple, mechanical means.

Rail Vehicles

Individual Cars, Locomotives, and Suspension Systems

The Division's Vehicle Dynamics Laboratory conducts experiments and tests on the dynamics and stability of rail vehicle bodies

and suspension systems, on the structural integrity and impact resistance of car bodies, and on the performance and durability of wheels, bearings, and brakes.

During the 1987/88, the Laboratory conducted strain surveys of rail vehicles under static, quasi-static, and dynamic load conditions for three car builders, *Thrall Manufacturing Co. (RoadRailer)*, *Fruehauf Corp.*, and *Bombardier Inc.* A prototype automobile restraint system for auto racks was tested on the Rail Vehicle Impact Ramp for *EIC Holden*. *CP Rail* contracted the Laboratory to measure stress levels occurring in inter-car drawbars during typical use, as well as participate in studies of the effect of wear on car stability.

A project was initiated under contract *VIA Rail Canada Inc.* to investigate the cause of premature roller bearing failures on a particular type of passenger coach. The railway wheel bearing test rig of the Engine Laboratory, and a suspension system to duplicate vehicle load transmitted to the bearing housing, were part of the test setup. Several combinations of different types of bearings and bearing housings were evaluated, using vibration as an indicator of bearing damage and temperature as an indicator of load transfer from the housing to the bearing.

The frame for the Wheel, Bearing, and Brake Research Facility was completed with machining assistance from *CP Rail* and was installed at the Vehicle Dynamics Laboratory Uplands site. Initial powering-up is anticipated for 1988/89. When completed, the rig will be used to study the highly-stressed brake, wheel, bearing, and rail system under closely controlled environmental conditions. Tribological effects of wheel and rail wear, now being studied at one-tenth scale by the Tribology and Mechanics Laboratory, will be correlated with the results of shorter duration, full-scale experiments on the Wheel, Bearing, and Brake Research Facility itself.

A distributed microprocessor control system was developed for the Laboratory's Curved Track Simulator (CTS). Specialized high-gain servo systems were designed and implemented on the CTS to maintain extremely small differential angular velocities between rollers in order to simulate curves. When available for initial use, projected for 1988/89, the CTS will provide Canadian

clients with several important simulator features that are unique in the world: the rail/wheel footprint will have a spin creep term adjustable to wheel conicity, and the wheels' footprints will be maintained exactly in a horizontal plane even if the wheelsets are yawed with respect to the track.

Dynamics of Trains

With the growing potential to apply computer modelling to the dynamic analysis and performance prediction of rail vehicles, the Systems Laboratory has begun to develop an extensive capability in this field.

During 1987/88 the Laboratory assembled an extensive collection of high-calibre software to model the activity of moving trains, and predict overall train behaviour and individual car dynamics within the train. Validation against experimental data was begun. Projects are being started in railway safety and wheel/rail wear.

Highway Vehicles

The Vehicle Dynamics Laboratory studies the behaviour of large road vehicles under both laboratory and field conditions. Analytical techniques are developed and used for advanced studies of stability and control, physical tests are carried out to determine rollover thresholds and to confirm model predictions, and measurements are taken to determine frame and suspension responses to dynamic excitations.

The off-tracking software model reported in 1986/87 was completed for use on personal computers. Designed to model complex articulated vehicles having up to four trailers, it will be used in conjunction with the turning templates of the *Roads and Transportation Association of Canada* (RTAC). The software will provide Canadian practitioners with a means of incorporating complex curves and pathways in road geometry.

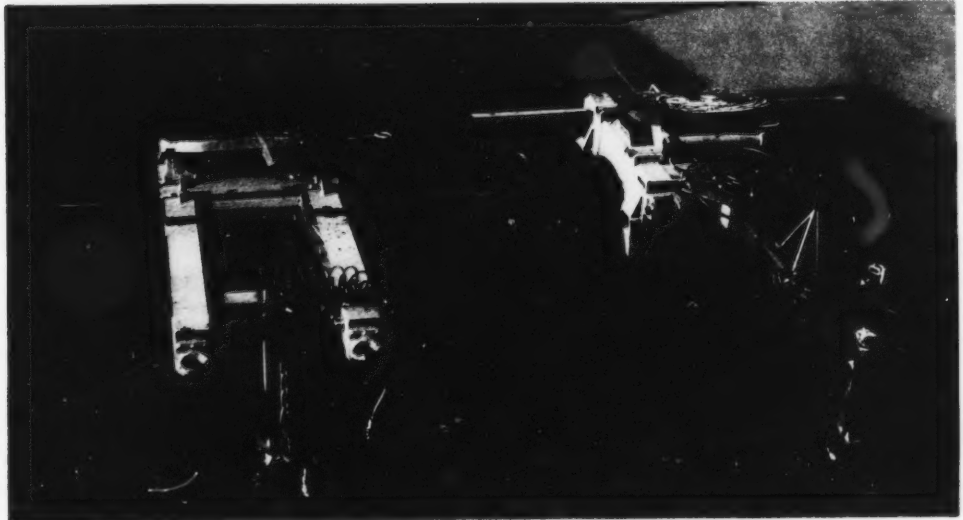
The Vehicle Tilt Table was further refined with the installation of a dedicated data acquisition and processing system. During 1987/88 the table was used to assess an

improved ambulance concept and to investigate the roll stability of an urban bus fitted with roof-mounted compressed natural gas storage tanks, for the *Ministry of Transportation of Ontario*. As well, the roll stability of a four-axle concrete mixer was measured for *Transport Canada*. The results of the latter test will be used to set parameters of test maneuvers for a full-scale stability and control experiment to be held in Vancouver.

Tests were conducted for the *Department of Transportation of New Brunswick* to determine the effectiveness of innovative tie-down methods for truck transportation of gypsum, to prevent load shifts due to lateral acceleration. In addition, the *Ministère des transports du Québec* was assisted in an analytical study of the effects of using a self-steering axle near the front steering axle of a dump truck, as opposed to using a synchronous twin steering system. The free castor steering axle concept had been proposed by the trucking industry as a relatively inexpensive means of attaining higher vehicle loading. Tests by the Laboratory showed that the concept would be unsafe.

A new test rig is being developed that is capable of measuring self-steering axle forces and moments, as well as roll steer, roll centre height, roll stiffness, and vertical stiffness. The rig is part of a study sponsored by RTAC's *Council on Highway Transportation Research and Development*. The purpose is to provide a sound technical base for the development of new provincial regulations for the C-dolly.

Demand for the Laboratory's expertise and facilities has increased sharply in the past year as a direct result of growing interest, by governments and industry, in the technical problems and opportunities of highway vehicle transportation. NRC is contemplating the establishment of an Institute of Road Vehicle Dynamics to help strengthen the Canadian capability. The institute would build on the existing NRC Road Vehicle Research Program in the Laboratory. With much of the capital infrastructure in place, including buildings and test rigs, the principal tasks would be to establish a corps of researchers and support staff, and to develop a research and service network in cooperation with national associations and with federal and provincial governments, universities, and the industrial sector.



A-dolly (left) and C-dolly for heavy highway trucks.

Enhanced Safety for Heavy Trucks

For nearly a decade, NRC's Vehicle Dynamics Laboratory has worked with Canadian truck manufacturers, regulators, users, and national associations to improve the performance and safety of heavy vehicles. In 1987/88, a new project was begun with the *Roads and Transportation Association of Canada* (RTAC) and the *Ministry of Transportation of Ontario* (MTO) to enhance the stability of multi-trailer trucks.

Multi-trailer trucks use dollies: wheels and axles in a frame that support the front end of the rear trailer and steer it through curves. For many years the "A-dolly" configuration has prevailed on Canadian roads. It incorporates two articulation points, a design feature that contributes to instability in the rear trailer during sudden truck maneuvers and that can cause trailer jackknifing, loss of control, skidding, and rollover.

In the mid-1970's a "B-dolly" configuration was developed in Canada that incorporates only one articulation point for better stability. Its use has increased steadily on tank trucks and flatbeds, but it is somewhat impractical for trucks that load through the rear.

More recently a "C-dolly" configuration has been developed that features a single articulation point and that has applicability to all kinds of trucks.

Unfortunately, the design considerations for a C-dolly are far more complex than for an A-dolly and, if improperly configured, it can have highly detrimental effects on the stability and handling of the vehicle. Until now there has been no comprehensive assessment of which of the many parameters governing C-dolly stability are most important and how they should be controlled, but in the meantime C-dollies have been growing in usage in some parts of Canada.

To meet the need of provincial authorities for technically-sound information on which to base regulatory decisions about C-dollies, RTAC's Council on Highway Transportation Research and Development (CHTRD) commissioned a project by DME's Vehicle Dynamics Laboratory and the Transportation Technology and Energy Branch of MTO to determine the importance of the various C-dolly parameters. DME and MTO are contributing personnel, expertise, analytical tools, and methodologies; DME is also providing the experimental facilities. CHTRD is contributing financially and has commissioned a steering committee for the project. It is anticipated that CHTRD also will organize follow-on work to develop codes of practice for designing, manufacturing, operating, and regulating the use of C-dollies.

When completed in 1988/89, the project will result in the technical base of information needed to ensure safety, along with maximum possible economy, in the use of C-dollies for heavy trucks on Canadian highways.

Propulsion Systems

Gas Turbine Engines

The Division's Engine Laboratory conducts research on propulsion systems, with emphasis on the overall or component performance of aircraft gas turbines, and on engine health monitoring and diagnostics.

Aero-Thermodynamic Engine Health Monitoring

An extensive review of analytical and experimental methods for determining compressor performance and health was conducted during 1987/88. New and in-service conditions were considered. Preliminary work in this field has been completed under a 3-year, AGARD-sponsored project with the *Greek Air Force Research Centre*.

As a means of integrating various fault and diagnostic models, a project was begun with NRC's Division of Electrical Engineering. An expert system was demonstrated for rotor balancing and a requirements study was begun for the application of artificial intelligence technology to engine diagnostics.

Development of cooperative studies and involvement in the preparation of standards has been pursued. Engine health monitoring support to the *Department of National Defence* was provided through the secondment of a Research Officer. Engine Laboratory staff participated in *The United States/United Kingdom/Canada/Australia/New Zealand Technical Cooperation Program* (TTCP) and the *Society of Automotive Engineers* international working groups. The final report of the TTCP group is expected later in 1988. A successful AGARD conference on engine health monitoring was also organized and hosted by the Laboratory.

Experimental Performance Assessment

Reports for the AGARD Uniform Engine Test Program were completed. Comparisons were made for the first time between altitude, ground level, and open-air test facilities; DME acted as the reference sea-level

agency. Thrust measurement techniques were rationalized as part of the work and reported in a Master's thesis by a DME staff member. Final reports on the program and on measurement uncertainty aspects are to be published in late 1988.

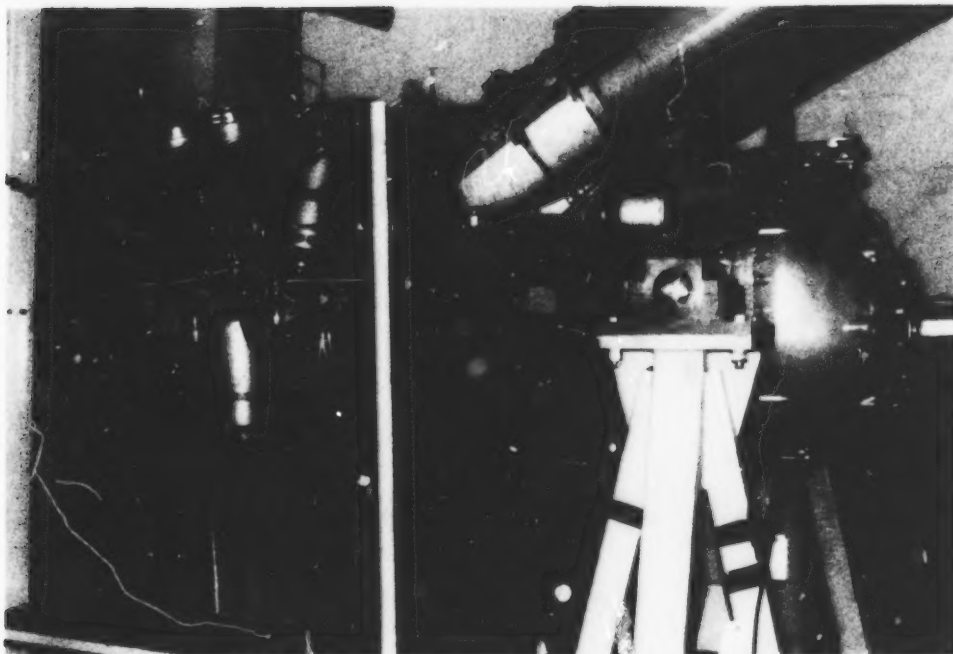
Under the sponsorship of AGARD, an engine performance correlation program was conducted with the *Turkish Air Force*. Concurrently, the No. 4 engine test cell facility at NRC was upgraded and recommissioned. Also during these tests, a commercially viable, automated data acquisition system was qualified for the *Department of National Defence* and the contractor *GasTOPS Ltd.*

The liquid fuel flow measurement capability of the Laboratory was improved by calibrations with the National Bureau of Standards and various North American facilities. As part of a proposal for a new National Facility, a plan was prepared for a liquid flow research and development rig for flow measurement and control devices. New sensor technology was acquired, and validation and integration studies of oil debris, gas path debris, and real-time thrust measurements were begun, the latter work with *Computing Devices Company*.

Propulsion Studies

Using the Engine Laboratory facilities, icing certification studies were conducted by *Pratt & Whitney Canada Inc.* on the *Aerospatiale ATR 72* propulsion system. As well, the Laboratory continued the validation of models and installation correction methods for advanced gas turbines, as part of international panels representing the *Department of National Defence*.

Studies supported by the Department of National Defence on erosion- and corrosion-resistant T56 blade coatings were suspended, pending coating development. Tests were carried out on both new and service-exposed T56 engines to provide data for compressor modelling and vibration investigations.



T56-A14LFE gas turbine undergoing baseline performance tests in DME's Engine Laboratory.

*Engine Condition Monitoring — Gas Path
Debris, Vibrations, and Acoustics*

Collaborators in this program include *Pratt & Whitney Canada Inc. (PWC)*, *Computing Devices Company*, *Stewart Hughes Ltd.*, the *Department of National Defence (Air Force and Navy)*, and *Rolls-Royce Limited (U.K.)*.

Work was initiated in the Laboratory to investigate and validate the technique of gas path debris monitoring to detect faults in a gas turbine engine. Several sensors developed by Stewart Hughes Ltd. were mounted in a T56 engine with the objective of detecting electrical charges of minute debris particles produced by the faults. Further work will involve ingestion of metallic debris from the intake and simulation of debris-producing faults such as blade rubs and combustor erosion.

The applicability of using vibration monitoring for engine condition monitoring is currently being studied. A 2-year program was

set up with PWC involving the use of the company's high-speed gear and bearing test rigs. Vibration and acoustic signals are being examined by seeding typically-occurring faults in test gears and bearings. The signals collected from the fatigue and endurance tests carried out by PWC are being analyzed to identify the change in the pattern of the signals over the operating life cycle of the components.

Work is also in progress on full-scale gas turbine engines. The use of existing techniques for extracting component vibration and acoustic signals (whose health is being monitored) from overall engine signals is being studied. Baseline data on T56 and F404 engines have been gathered and the visibility of the vibration signals from bearings and gears is being examined. Plans are underway to implant faults in a T56 engine, which is currently being rebuilt.

Advanced Gas Turbines — Highly Loaded Blading

Following an earlier failure of the experimental turbine test rig, some components were redesigned and the rig was rebuilt replacing the S1 with the 3DS nozzle and the 45 with the 51 blade rotor. Research was then resumed, measuring interaction between the nozzle passage flow and the probe. To simplify certain experiments, perforated steel plates were designed and built for simulating rotor presence with respect to total pressure loss and flow turning. The interaction effects between these plates and the nozzle have been measured and are to be compared with those due to the blade rotor. The results of the above studies are the subject of a research paper currently under preparation.

The next objective of this project is to investigate how aerodynamic stage performance for different blade loadings is influenced by tip clearance effects. The clearance will be altered in two ways: by shaving the blade tips and by varying the inner diameter of the turbine casing. Plans are also in place to test a turbine demonstrator stage for validating the computational fluid dynamic models used by industry to design gas turbine products. The initial tests involve a new nozzle assembly embodying recently developed features for improving stage performance.

Reciprocating Engine Technology and Fuels

The Division's Fuels and Lubricants Laboratory is concerned with research in reciprocating engine technology, engine fuels and combustion, fuel safety issues, and petroleum product standards and testing.

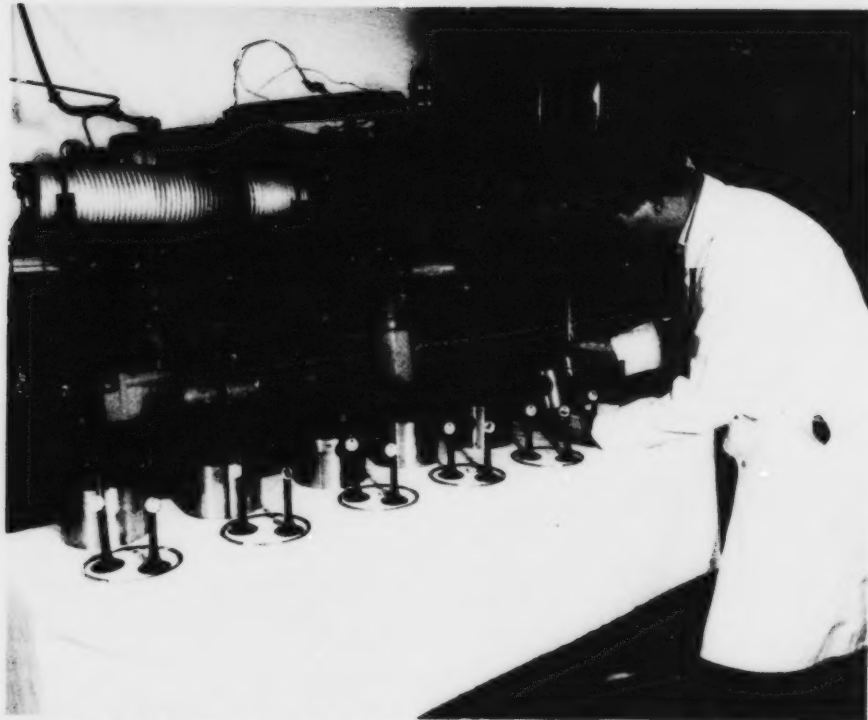
Combustion and Engine Performance with Alternative Fuels

The research project aimed at determining the effect of low-ignition diesel fuel on the combustion performance and durability of commercial and military diesel engines continued in 1987/88 and will be completed by

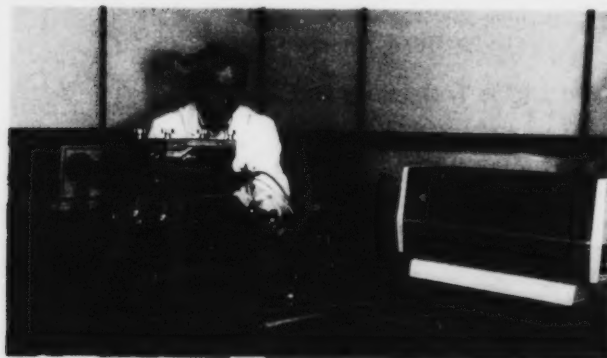
1989. Using blends of hydrotreated cat cracked cycle oil and diesel fuels containing tar sands components as worse case fuels, the effect of poor ignition quality and high sulfur fuel on performance was measured. A recently-completed, 500-h test with 35 CN fuel in a Cummins NTC 400 showed little effect on performance. Wear and deposits on the dismantled engine appeared satisfactory and are being quantitatively assessed. A similar 500-h fuel test in a Detroit Diesel Co. 6V92TA turbocharged diesel engine showed significant fire ring wear. The wear was confirmed using a novel approach in which the chromium content of the oil (from the fire ring) is monitored in a series of much shorter (6.25 h) durability tests. The wear can be correlated with the instantaneous rates of pressure rise; however, modification of the engine ignition characteristics in the shorter tests showed potential for reducing these rates.

As diesel combustion particulates are a major environmental concern, a mini-dilution tunnel was used to monitor such particulates from all in-house engine tests. A 20% increase was recorded with the Cummins NTC 400 when operating on 35 CN fuel compared with a reference fuel of >40 CN. The individual influence of sulfur, high aromatics, and end point on particulates has not been isolated. Cooperative work underway with *Energy, Mines and Resources Canada* and *Transport Canada*, which is aimed at assessing the propensity for particulate formation of a matrix of fuels covering a range of sulfur and aromatic contents, will hopefully provide this information.

The use of ceramic components to permit reduced heat rejection from a single-cylinder diesel engine has enabled compression temperatures approximating the ignition temperature of hydrogen fuel to be attained. Recent experiments with gaseous hydrogen injection have produced ignition and the engine test system will now be modified to provide a continuous running capability.



Pistons and valves from Cummins NTC 400 diesel engine after 500-h durability experiments with 35 CN fuel.



Drop-size measurement of transient diesel sprays by laser light scattering in a combustion bomb.

Combustion Diagnostics and Effects of Fuel Sprays

Essential data were collected to validate an alternative inversion algorithm that is being developed, to reconstruct the drop-size distribution from forward scattering light data of the laser light diffraction system.

An investigation of soot formation in diffusion flames by laser light extinction showed that flame radiation and exhaust smoke can be correlated to the smoke point and H/C ratio of middle distillate fuels. Experiments with several hydrocarbon blends with the same H/C ratio confirmed that soot formation in diffusion flames is controlled by fuel molecular structure and flame temperature. This work is being extended to cover diesel engine soot formation (particulates) with financial support from *Energy, Mines and Resources Canada*.

Fuel structural information derived by advanced analytical techniques was used to support all fundamental and engine combustion research. The sooting propensity of aviation fuels and the ignition quality of heavy marine diesel fuels are two studies in which structural data played an essential part.

The KIVA computer code will be used to model reciprocating engine combustion, after it has been modified for the NRC IBM mainframe computer. At present, cold-flow and premixed homogeneous gaseous fuel charge combustion can be modelled. A gasoline engine was modified to operate on propane and will be used for the computer code validation.

Advanced Structural Materials in Diesel Engines

An exhaust valve with a Si_3N_4 ceramic wafer in the seat face, designed and built by the Division's Manufacturing Technology Centre to extend valve life and avoid erosion during residual fuel combustion, was evaluated in the Laboratory's Bombardier B-2400 medium-speed single-cylinder research engine. The valve completed 74 h of endurance testing prior to failure, exceeding expectations for the first prototype. It is estimated that the material capabilities of the

next prototype can be doubled by residual stress reduction. This work is partially funded by the *Association of American Railroads*.

An experiment, funded by *Alcan International Ltd.*, to install and operate a ceramic/ceramic composite lobed camshaft and followers in a Deutz F1L511D diesel engine was successful. This was the first time that a monolithic composite ceramic camshaft had been employed in a diesel engine. Alcan-funded durability experiments will continue and extend to include ceramic valve seats.

Initial steps were taken by NRC to form a consortium of companies working with *Bombardier Inc.* to develop prototype ceramic components for engine wear applications. The Fuels and Lubricants Laboratory and other NRC groups will assist the consortium members.

Diesel Engine Health Monitoring

The instantaneous crank angle velocity (ICAV) technique for monitoring diesel engine health was evaluated using the Laboratory's Bombardier B-251 12-cylinder medium-speed diesel engine at full speed and full load conditions. Results showed that a 5% change in an individual cylinder pressure could be detected to within $\pm 6\%$ and $\pm 3\%$ at low speeds and low loads, respectively.

Vehicle Regenerative Power Systems —City Bus Application

In addition to a 17% net lower fuel consumption measured on a city bus equipped with a prototype regenerative power system, a major advantage anticipated is the associated reduction in exhaust emissions, of which diesel particulates are the most critical. To confirm this advantage, the bus was tested on the unique chassis dynamometer facility at South West Research Institute, San Antonio, TX. Preliminary data analysis indicated a larger than anticipated reduction in particulates. A demonstration program, with a small number of the system-fitted buses operating in revenue service, is in the planning stage.

Standards and Testing of Petroleum Products

Standards activities have been essentially limited to providing support to standards writing bodies such as the Standards Council of Canada, the Canadian General Standards Board, the International Organization for Standardization, and NATO. Laboratory personnel serving these organizations provide expertise, derived from laboratory projects necessary for the preparation and maintenance of optimum quality standards.

Methods for measuring the ignition quality of diesel fuels and heavy marine fuels and the constant compression modification of the engine-measured CN method are examples of such input. The identification of standards and classifications of the International Organization for Standardization to be recommended to the Standards Council of Canada for adoption is a current laboratory activity and offers advantages for international trade agreements.

Product testing and evaluation in support of internal and external activities continued and included revenue projects for industry and other government departments, where facilities/expertise peculiar to the Laboratory were required.

Fuel Handling and Safety

An evaluation of field test kits for measuring the volatility of gasoline was made for *Transport Canada*, as part of the their program aimed at providing limited approval for the use of automotive gasoline in light piston engine aircraft. The Laboratory continued to receive funding from the *Canadian Aviation Safety Board* for the examination of aircraft fluid and other samples from aircraft accident investigations. The number of samples

examined in 1987/88 was triple that of the previous year.

The gelled fuel combination developed by the Laboratory for the torches in the XVth Olympic Winter Games met all specifications set by *Petro-Canada*, the sponsor and organizer of the Olympic Torch Relay. Because of its inherent safety and absence of excessive smoke when burning, the fuel was used for ceremonial occasions and during the nightly medal awards at the Olympic Plaza.

Ricardo Hydra Fuel Tests

The Engine Laboratory, in related reciprocating engine studies, compared normal No. 2 diesel fuel and a tar sands derived diesel fuel in the direct injection single-cylinder Ricardo Hydra test engine. In smoke-limited power tests with the engine optimized for No. 2 fuel, it was found that the tar sands fuel gave less midrange and peak power. Lowest speed, brake-specific fuel consumption was the same, while the tar sands fuel consumption was lower at high speeds. Tar sands fuel resulted in higher cylinder pressure with greater variation from cycle to cycle and also longer pressure delays. At speeds above 30 rev/s, the tar sands fuel produced lower emissions of carbon monoxide, while nitrous oxide emissions were higher at all speeds. Hydrocarbon emissions from tar sands fuel were higher at low and high speeds. Reports covering this work are in preparation.

The Ricardo Hydra test engine will be used for upcoming engine health monitoring projects. The application of electrostatic sensors (developed for gas turbine monitoring) for detecting pulsed exhaust of a diesel engine will be studied.

Fluid Dynamics and Combustion

Work in the Gas Dynamics Laboratory is aimed at particular aspects of continuous combustion, transonic heat transfer, internal aerodynamics, and novel mechanisms of water jet cutting, which share a common dependency on expertise in thermodynamics and fluid mechanics. The research is assisted by, and closely interwoven with, work on the development and validation of specialized computer codes for prediction and design.

The overall experimental effort is supported by the operation of the Compressor/Exhauster Plant, which supplies air to other facilities designed for research on continuous combustion applications, internal aerodynamics, and complete propulsion systems operated at simulated forward speed or under icing or altitude conditions. Operation of the Plant not only supplied air to the Engine Altitude Experimental Facility, but also to the Propulsion Wind Tunnel, Engine Icing Test Facility, turbine research rigs, and combustor rigs.

The Compressor/Exhauster Plant saw increased utilization in industrial projects. Problems with commissioning of the new 8-MW compressor continued, and increased emphasis therefore was placed on refurbishing and updating the existing 2-MW exhauster and 5-MW compressor.

A new aftercooler, furnished by Pratt & Whitney Canada Inc. (PWC), was installed in the Engine Altitude Experimental Facility. PWC also installed a second test chamber of increased dimensions and contributed considerable manpower and other equipment to the new arrangements. Air supply to the cells can now be driven by a low-capacity fan, a high-pressure air ejector, the 2-MW exhauster, or the 5-MW compressor, depending on test requirements relating to flow rates and altitude simulation.

Two industrial projects were completed in the Propulsion Wind Tunnel, one each for PWC and Canadair. A new inlet screen, revised gearbox instrumentation, and reconditioned gas turbine starter unit were installed during 1988/89.

Continuous Combustion Processes

The advent in the past decade of noninvasive measurement techniques such as laser Doppler anemometry, laser-based drop-sizing methods, and coherent anti-Stokes Raman spectroscopy (CARS), together with vastly increased computational powers, has led to important developments in the measurement, understanding, and prediction of combustion processes. Application of these new experimental techniques permits the validation and extension of numerical methods for combustor design and performance prediction, and the resulting expertise has already proven useful in many practical areas.

During the past year, work was carried out for and with Canadian companies in such areas as emissions reductions through combustor design and water injection (Westinghouse Canada Inc. industrial gas turbines), atomizer design for prescribed characteristics (PWC, Parker Hannifin (Canada) Inc.), and burner analysis and measurements for spraying of plastic droplets (Cortech Systems Ltd.). The high-pressure combustion rig continued to yield valuable engine test results for PWC. The seven-atmosphere research combustor has been instrumented and work has begun on an alternative fuels program for the Department of National Defence.

Strategic work continued with the development of flow/spray visualization techniques aimed at measuring two-dimensional flow fields in seeded combustions flows, and droplet size and velocity in sprays. Two separate systems, which permit several possible experimental configurations, were designed, built, and demonstrated.

The Laboratory's CARS system for measuring flame temperature was redesigned and reassembled in a more compact form suitable for making measurements in atmospheric burners and high-pressure combustors. NRC-developed software for temperature prediction was compared with a code from Sandia, with excellent agreement (within 1 K at 1550 K) despite significant differences in methodology. Current work



Measurement of temperature in flame by CARS. Data from this experiment will be used to validate computer-based computational fluid dynamics models.

consists of applying the CARS technique to temperature measurements in a research burner.

Computational Fluid Dynamics and Thermodynamics

Work in this area is closely linked to experimental research in combustion and internal aerodynamics. A development of a 3D-TEACH code was implemented to include gaseous combustion and used in *Cortech* burner development. Validation is being performed through cooperative work with PWC. Further work is underway to include complex chemical kinetics and liquid spray combustion in the Laboratory's computational fluid dynamics project.

Aerodynamics work included the prediction of vortices resulting from the interaction of a turbulent boundary layer and surface-mounted obstructions. Collaborative research is underway with PWC to extend this approach to practical situations (e.g., the flow around turbine nozzle guide vanes at high Mach numbers) and to the prediction of heat transfer effects. Other code development work addressed turbulent mixing of

confined coaxial streams, and successful predictions of experimental results have been demonstrated.

Internal Aerodynamics and Heat Transfer

The planar cascade facility, constructed to allow the investigation of transonic heat transfer in a turbine nozzle passage, is operational. Results are expected to shed light on unexpected findings of previous turbine investigations and to have broad application in the interpretation of experimental data.

Financial support from the NRC President's Fund has allowed the establishment of a three-stage research project designed to ascertain the feasibility of determining local heat transfer using a high energy laser. Work is well underway on the first two stages. The research team is composed of an NRC researcher, and a professor and Master's student from Queen's University. A three-dimensional heat transfer code was written to simulate the phenomenon. Results from preliminary analysis confirmed the validity of the concept, which could be of general use in many industrial situations.

High-Speed Water Jet Technology

Work undertaken during 1987/88 consisted of drilling, fragmenting, and slotting of hard rocks with rotating high-pressure (140 MPa) water jets, with and without mechanical assist, and the study of the effect of physical properties of rocks on the rates of penetration. Although the penetration rates at 140 MPa in the samples were very encouraging, they were still below those required by mining companies. Attention was, therefore, focused on the design of a rotating abrasive-entrained water jet system. (This work was pursued by a visiting scholar from China, sponsored by the World University Service of Canada.) A preliminary design was completed and testing is in progress in the Laboratory.

In support of an IRAP technology project, the Laboratory worked with *Indescor Hydrodynamics Inc.* in the manufacture of rock-slotting and roof-bolting machines for mining and quarrying applications. The prototype rock-slotting machine was completed and field-tested in October 1987.

Research on cavitating water jets continued in the Laboratory. A flow visualization study using laser and stroboscopic lighting, pursued by a postgraduate student from the University of Ottawa, was completed. In other work, photography of submerged water jets (in a pressure vessel) showed the effect of ambient pressure on the process of cavitation. These investigations clearly indicated the need for further research in this area. Design and fabrication of the ultrasonic nozzle to produce cavitating or pulsed jets is in progress.

Cold Regions Engineering

The Low Temperature Laboratory conducts a research program covering a spectrum of thermodynamic problems that exist in the operation of engineering equipment and thermal systems in a temperature range typical of Canada's boreal climate and its coastal and offshore environments. The program focuses on heat transfer and heat

exchange, heat pumps for industrial and commercial application, ice accretion and removal from structures and system components, snow ingestion problems and their avoidance (with emphasis on the transportation sector), and the testing of engineering equipment to meet climatic standards, as well as the maintenance and operation of National Facilities to undertake these experimental and testing projects.

Heat Pumps

The 50-kW, steam-generating, heat pump test facility was commissioned and performance trials are now in progress. Preliminary test results were encouraging and have identified areas where component modifications can improve overall system performance. When the unit is optimized, expected in 1988/89, long-term durability testing work and the experimental program to investigate high-temperature refrigerant/synthetic oil lubricant combinations will begin.

A test facility recently was completed for the purpose of investigating nonazeotropic refrigerant mixtures. This new experimental program is aimed at increasing cycle efficiencies of heat pumps operating at high temperatures and investigating the thermodynamic performance of environmentally acceptable substitutes for the refrigerant chlorofluorocarbon. The facility is instrumented to provide information on the behaviour of mixed refrigerants, particularly in heat exchangers.

Heat Transfer

The cooperative research program with *Atomic Energy of Canada Limited* to develop a passive, safe-decay, heat release system for the SLOWPOKE reactor has now achieved several goals. A prototype thermosyphon was installed in the 2-MW pilot reactor at the Whiteshell (Manitoba) Nuclear Research Establishment. A stainless steel version of the thermosyphon, for use in a future reactor of 10-MW capacity, was

tested and demonstrated a 40% capacity increase over the required value. This translates into a considerable benefit to the final reactor implementation where reliability in an emergency is vital. The thermosyphon uses no electrical power and there is no possibility of mechanical failure. Work continues on performance enhancement through extended heat transfer surfaces and surface treatments.

A new program was initiated in computational fluid dynamics (CFD) and heat transfer, directed towards the numerical simulation of transport phenomena in heat exchangers. The general purpose CFD code PHOENICS was installed and commissioned on a DEC VAXstation 2000. The code is now being used to simulate laminar/turbulent fluid flow and heat transfer in typical elements of bundles of cylindrical rods. The work is presently confined to steady two-dimensional, single-phase cross flow for staggered and in-line configurations using a curvilinear "body-fitting" coordinate system. In the coming year, attention will be directed towards the more general three-dimensional case. The simulation capability may be applied to a wide range of engineering problems involving combustion, fluid flow, and heat and mass transfer.

Environmental and Climatic Effects on Industrial Equipment

Phase II of the refurbishment of the large refrigeration system was completed. This serves the Icing Tunnel of the Low Temperature Laboratory, as well as the Engine Icing Test Facility of the Engine Laboratory. Downtime was minimized and the Icing Tunnel was able to continue operation to serve both the internal research program and several external clients, including *Leigh Instruments Limited*, the Atmospheric Environment Service of *Environment Canada*, and the U.S. Army. Modifications to improve tunnel environmental conditions were achieved. The internal research program concentrated on the heat transfer characteristics of roughened surfaces, typically found with icing phenomena on engineering equipment.

The Helicopter Icing Facility was utilized by the Aeroplane and Armament Experimental Establishment of the Royal Air Force (RAF)

of Boscombe Down, U.K., as part of the RAF's extensive cold weather trials conducted at several Canadian locations over the winter. This was possible through assistance from the Department of National Defence as part of Canada's NATO contribution.

Using the Climatic Engineering Facility, the Laboratory assisted in a thorough examination of the heating, ventilating, and air-conditioning systems of an urban transit rail car, built for export by *UTDC Inc. Delta Engineering*, a Canadian company with a worldwide reputation and sales record for snowmaking equipment, investigated new snow nozzle technology in a small cooperative program. The *Department of National Defence* (through the Land Engineering Test Establishment) continued to use the Facility for extensive testing of the cold weather performance of military equipment of a very broad range.

To evaluate the performance of mechanical systems compromised by snow conditions, the Low Temperature Laboratory developed the capability to produce artificial snow in the Climatic Engineering Facility at any time of the year. During 1978/88, research was conducted to improve the Laboratory ability to control the most important properties of the artificial snow. A study was carried out to determine snowfall rate, involving measurement of snow accumulation to an identifying dyed layer over a specified time interval.



Dye injection technique for snow-making evaluation.

Coastal and Offshore Engineering

Coastal Engineering

The Division of Mechanical Engineering's Hydraulics Laboratory specializes in physical, mathematical, and hybrid modelling of the coastal environment, including the effects of waves and currents on shoreline erosion and on coastal structures.

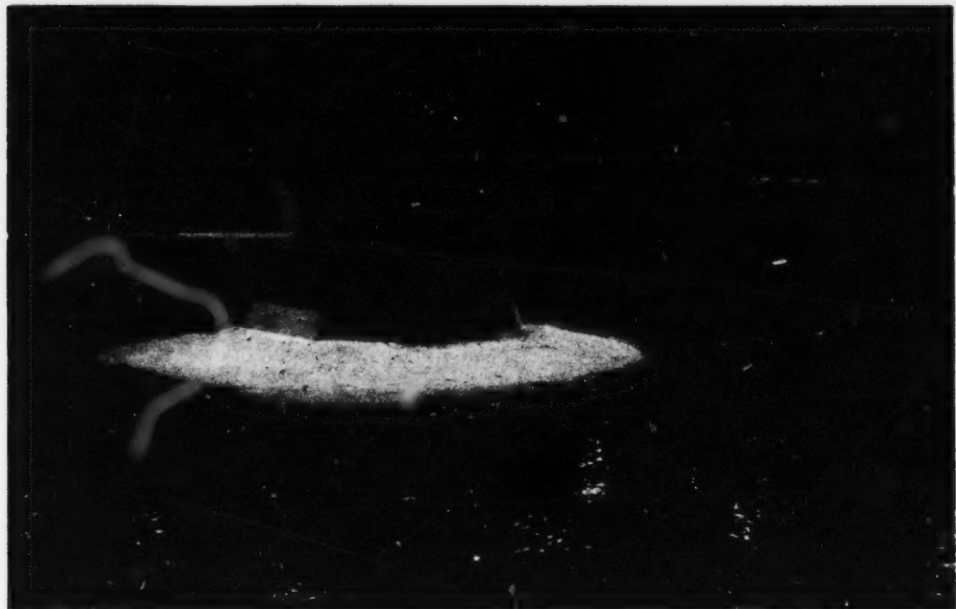
The unique facilities in the Hydraulics Laboratory, for modelling coastal areas in shallow water wave basins, were used in 1987/88 by engineers from *Public Works Canada* to study breakwater orientation and stability for small-craft harbour developments. Six such harbours in Newfoundland were designed and tested.

As well, samples of a clay-like dense till from Northumberland Strait were tested for Public Works for their erosion threshold under the action of water current shear. A laser Doppler velocimeter was used to measure

the velocity profile and shear. This information may be used to optimize the design of scour protection around bridge piers for a proposed Northumberland Strait crossing between New Brunswick and Prince Edward Island.

W.F. Baird and Associates Coastal Engineers Ltd. carried out six model studies involving berm breakwater design, beach development, and harbour inlet and shore protection schemes. These various studies occupied the Coastal Wave Basin and the 14 x 28 m wave basin.

The 30 x 30 m shallow water wave basin was modified to provide water flow at $2 \text{ m}^3/\text{s}$ to generate currents, in addition to waves, for a W.F. Baird and Associates' study of wave- and current-induced scour of the berm on which an Arctic caisson drilling platform is located. The model tests identified the areas of potential erosion of the berm foundation, allowing preventive measures to be taken.



Identifying areas of wave- and current-induced erosion on the berm foundation of an industrial model caisson proposed for Arctic resource exploration.



Model tests of a rubblemound breakwater in one of the basins of the Hydraulics Laboratory.

Development of Improved Coastal Engineering Test Methods

In a recent study, *W.F. Baird and Associates Coastal Engineers Ltd.* contracted a foreign laboratory to perform model tests in which deep-water storm waves were propagated up a slope into a shallower water zone where a rubblemound breakwater was to be located. The objective of this study was to identify the deep-water sea state that would result in the most severe wave anticipated to break on the structure and then to design the structure to withstand this impact. The foreign laboratory found that such worst conditions could be induced in shallow water by a deep-water wave climate representing that which occurred approximately once in 100 years at the site under investigation. The design was therefore considered to be safe since the breakwater would rarely be subjected to such severe waves.

The study was subsequently repeated in collaboration with DME's Hydraulics Laboratory and tests were run in the Coastal Wave Basin using a similar bathymetry. However, to the surprise of W.F. Baird and Associates and NRC researchers, the generation of a relatively smaller deep-water wave climate — which occurs several times every year — was propagated up the slope and impacted on the structure with the same energy as had been measured for the 1-in-100 year storm! This difference in frequency of occurrence had a significant influence on the breakwater design and cost, since it would have been unacceptable to design the breakwater for conditions expected once in 100 years and then expose it to these conditions much more frequently. The frequent occurrence of this severe wave

climate could lead to a slow degradation of the breakwater and an eventual failure.

The large discrepancy between the two laboratory findings about the deep-water wave climates needed to propagate the design wave conditions to the structure was found to result from differences in the wave generation methodologies used by the two laboratories for the study. Because of the far-reaching implications of this finding, DME staff undertook collaborative research with W.F. Baird and Associates to develop a better understanding of the observed results and ultimately to define a better testing methodology for shallow water structures.

The collaborative study has now shown that, for a given deep-water sea state defined solely by its energy content, a large number of wave trains can be simulated with slightly different characteristics. The sequence of high and low waves in the various wave trains has proved to be important: different wave trains propagate differently on the slope and induce varying degrees of breaking. This causes an extraordinary range of shallow water wave conditions. Because of this unexpected major discovery, NRC has adopted a new testing procedure that involves experimenting with various deep-water wave trains to find the one which propagates the most severe wave conditions to the structure. The design of the structure is then optimized using that particular wave train.

The novel NRC findings, already being disseminated through international conferences, are expected to create awareness of this problem in the coastal engineering community at large and will help NRC clients design more durable and cost-effective structures.

The Multidirectional Wave Basin was used in 1987/88 for two shallow water coastal engineering studies. The first involved developing a novel beach protection scheme and recreation area for Highland Park, north of Chicago, in a project by *W.F. Baird and Associates*. The readiness with which the segmented wave generator could be programmed to send long-crested waves from different directions towards the model beach allowed the company to discover a critical direction for sand transport, which would not likely have been found otherwise. The second coastal study in the Basin was of St. Shott's Harbour, Nfld. Engineers from *Public Works Canada* carried out tests to determine the shape, size, and stability of a rubble-mound breakwater, armoured with concrete Antifer cubes, for storm waves from several directions.

In cooperation with NRC's Institute for Marine Dynamics, the Hydraulics Laboratory carried out physical model tests in the 14 x 28 m wave basin, of the performance of the floating pontoon ferry terminal located at Bar Harbor, ME. For the sponsor *Marine Atlantique - Marine Atlantique* of St. John's, Nfld. (operator of the ferry and terminal), NRC was required to find ways to reduce the motions of the pontoon in waves and to decouple or prevent such motions from twisting the connecting bridge compared with the shore. These objectives were met. In addition, the impact energy of the pontoon on its constraining piles was measured to allow the client to redesign the fendering structure.

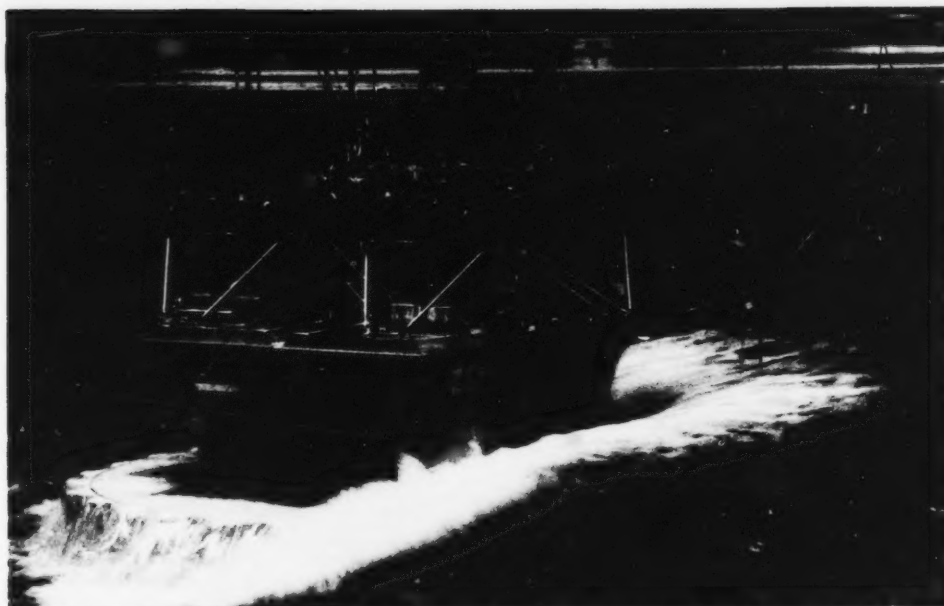
During the 1987/88, generic research was carried out for *Canada Oil and Gas Lands Administration* to study wave-induced pore pressure in, and scour and stability of, sand berms on which caisson drilling platforms are placed. The tests were performed at several scales in the wave channels. This continuing study has already demonstrated the importance of testing with larger waves, which yield dramatically different results from the smaller scale tests. Analytical predictions of the steady-state berm response, as well as of liquefaction failures, have been improved by comparison with the observed berm behaviour.

Offshore Engineering

The Hydraulics Laboratory generates realistic sea states in its basins to enable offshore structures such as drilling rigs, caissons, and guyed towers to be accurately subjected to environmental forces of waves, currents, and winds.

The Multidirectional Wave Basin, formerly called the Offshore Wave Basin, is mainly used for model testing of offshore structures in deep water and for wave generation research. A new technique was developed in 1987/88 for creating a larger useful test area in the Multidirectional Wave Basin. The technique involves using the short side walls adjacent to each end of the segmented wave machine to reflect waves back into the area of interest, thus creating "virtual" wave board segments at both ends of the 60-segment machine and thereby effectively increasing its size to considerably more than 60. Other similar wave basins now in use or being designed may achieve a comparable increase in their useful working area, at little extra cost.

In 1987/88, the Basin was used to carry out a large study on wave runup and forces on the column deflectors and cellar deck of a gravity-base offshore oil production caisson, proposed for use at Hibernia, east of Newfoundland. The work was carried out by the Laboratory for *Mobil Oil Canada, Ltd.* and its joint venture participants: *Chevron Canada Resources, Limited; Gulf Canada Resources, Inc.; Petro-Canada Resources, Inc.; Columbia Gas Development of Canada, Ltd.* Concurrent with this testing, researchers from NRC's Institute for Marine Dynamics studied the maneuvering of a support vessel in adjacent waters to the caisson. A 1:40 scale model vessel, equipped with bow and stern thrusters in addition to its two main screws and rudders, was to maintain station alongside the caisson under increasingly severe conditions of short-crested seas, as well as winds.



Model of a gravity-base, oil production caisson undergoing tests for a client in controlled wave and wind conditions.

Circular cylinders, pipes, and caissons make up the structural members of most offshore oil and gas exploration and production platforms. In cooperation with two graduate students from the *University of British Columbia*, a study was carried out on the wave forces on a fixed vertical circular cylinder of 0.17 m diameter and 2.4 m height, in 2 m of water. The test conditions included regular and irregular long- and short-crested waves. The Morison equation was found to model the wave forces on the pile quite accurately for regular waves, particularly when the average force coefficients over the entire pile were used. Even for the tests in narrow-band short-crested seas, the spectra of force distributions were predicted well by nonlinear theory.

The same segmented vertical cylinder was used to simulate a tower structure on a compliant foundation. In collaboration with

a researcher from the *University of Melbourne*, Australia, the frequency- and time-dependent force coefficients for the dynamically responding cylinder were determined for long- and short-crested wave excitation. The experiments confirmed the proposition that there will be decreased hydrodynamic damping with a decreasing ratio of cylinder resonant frequency to peak wave frequency.

In cooperation with a scientist from the *University of Grenoble*, France, basic research on the generation and propagation of solitons (solitary waves) was carried out in two shallow basins. The generation technique developed at NRC will permit the study of internal waves that can occur wherever there is marked stratification of water with depth, either in terms of temperature or salinity.



Segmented wave generator: several segments during installation (left) and the full array in operation (above).

Development of a Segmented Wave Generator

Researchers in coastal engineering and naval architecture have produced waves in their laboratories for at least 50 years. Unfortunately the early wave generators, being rudimentary motor- and crank-driven oscillating boards, were inherently limited to generating only regular waves, which are not representative of the natural sea. Short-crested (multidirectional) waves must be reproduced to give a realistic simulation of the natural sea. To do so requires construction of a "segmented" wave maker with computer-controlled wave-making boards.

Only in recent years has this been attempted. In 1982 NRC decided to acquire a short-crested wave-making capability, but none of the commercially available machines had either the capabilities or features needed to make such a system practical for the range of anticipated experimental and commercial testing. Because of their extensive prior experience in the construction of regular wave generators, W.R. Davis Engineering Ltd. of Ottawa and DME's Hydraulics Laboratory decided to design and construct a segmented wave machine to suit the Laboratory's needs. This venture was made feasible by the mechanical engineering design and fabrication skills of Davis Engineering and the hydrodynamic and computer software expertise of the Hydraulics Laboratory.

The resulting segmented wave machine came into operation in 1985. Built in Canada, it has a number of outstanding features that provide the Hydraulics

Laboratory's clients with high-level capabilities and that make the machine a good commercial prospect for Davis Engineering. The features include

- highest power level of any wave-making machine of its kind in the world
- capability for vertical relocation to permit a variety of different water depths
- easily modified wave board displacement modes for rotational or translational movement
- optimum performance for a wide band of frequency ranges of the wave spectrum
- total direct digital control system for each segment.

The installed wave maker provides the Hydraulics Laboratory with a capability for testing models at a wider range of scale factors than can be done at any other institute in the world.

Some of the features have been patented and licensed to W.R. Davis Engineering Ltd. for commercial exploitation. The company is now building an enhanced, 192-segment version of the machine for NRC's Institute for Marine Dynamics in St. John's, Nfld., and incorporating specially developed computer software for the production of waves with a directional spread of nearly 180 degrees, by exploiting the simultaneous use of generator segments on three adjoining walls of the tank. The company is also pursuing foreign markets and is a strong contender for several new installations because of the wave maker's outstanding capabilities and its proven record in service at NRC.

For the expected oil field development at Hibernia and at Terra Nova, it is important to gain an understanding of such internal waves and their interaction with structures (e.g., shearing of rig riser pipes). In cooperation with researchers at the University of Grenoble and scientists at the *Bedford Institute of Oceanography*, Dartmouth, the Hydraulics Laboratory expects to construct a special wave flume in which internal waves and large surface waves can be generated and their interaction can be studied. This study may even contribute to an understanding of whether the occurrence of unexpectedly large surface waves, called freak waves, is associated with the presence of large internal waves.

The Hydraulics Laboratory's cold chamber basin was used to study offshore structures in a simulated moving ice cover. The work covered basic and applied research on ice cover and structure modelling techniques. Several projects were sponsored by the federal government's *Panel on Energy R&D* (PERD) through the Public Works Canada's Ice/Structure Interaction Program. Model tests were performed to investigate how the

loads or forces of an ice rubble field grounding on a berm are transferred to the berm and to the caisson island sitting on it. Researchers from NRC's Institute for Research in Construction participated in this work. Further tests are planned to investigate the load apportioning with refrozen rubble.

The Laboratory also made an investigation, for PERD and Public Works Canada into the effect that flaws or cracks in an ice cover have on narrow structures, when the cover is failing against it. The effect of flaw shape, length, and number per unit area were studied, as well as structure shape, aspect ratio, and indentation rate. The results showed that only very few large ice-cover flaws were required for producing a very large reduction in the load that the cover transmits to the structure. These findings may help to explain the longstanding discrepancy between model and prototype tests of ice loads on structures. Typically the loads on full-size structures were not as high as predicted from model tests. Field observations may be necessary to further develop the Laboratory's new theory.

National Facilities of the Division of Mechanical Engineering

National Facility	Contact	Telephone	Fax
Anechoic Engine Test Facility Engine Icing Test Facility Calibrated Gas Turbine Test Facility	D.M. Rudnitski	(613) 993-2425	(613) 957-3281
Compressor/Exhauster Plant Combustor Development Facility Propulsion Wind Tunnel Engine Altitude Experimental Facility	R.G. Williamson	(613) 993-2442	(613) 952-7686
Coastal Wave Basin Multidirectional Wave Basin	B.D. Pratte	(613) 993-2417	(613) 952-7679
Climatic Engineering Facility Icing Tunnel Helicopter Icing Facility Heat Pump Calorimetric Facility	I.R.G. Lowe	(613) 993-2439	(613) 954-1235
Vehicle Vibration Facility Vehicle Squeeze Frame Rail Vehicle Impact Ramp Wheel, Bearing, and Brake Research Facility Curved Track Simulator Vehicle Tilt Table Truck Suspension Measurement Facility	C.A.M. Smith	(613) 998-9638	(613) 957-0831
Hardware-in-the-Loop Simulation Facility	V.J. Thomson	(613) 993-9461	(613) 952-7686

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